Millimeter-Wave Wireless Power Transfer Technology for Space Applications

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Introduction

Technologies enabling the development of compact systems for wireless transfer of power through radio frequency waves (RF) continue to be important for future space based systems. For example, for lunar surface operation, wireless power transfer technology enables rapid on-demand transmission of power to loads (robotic systems, habitats, and others) and eliminates the need for establishing a traditional power grid. A typical wireless power receiver consists of an array of rectenna elements. Each rectenna element consists of an antenna together with a high speed diode and a storage capacitor configured in a highly tuned narrowband circuit for this purpose. The conversion of the microwave energy into DC in this fashion is almost instantaneous. Using a high power rectenna array in concert with a fast charging high performance battery can enable charging of the battery at very short time with a large power burst and discharge of it at a lower rate for an extended operation time for remote electronic assets.

Two main factors that determine the physical size of a rectenna based microwave power conversion system are the frequency of the RF transmission and power capacity. At higher frequencies, the size of the antenna elements in the array is small resulting in a smaller form factor for the system. The smaller form factor of the higher frequency wireless power receiver makes them more attractive for space systems; however, higher frequency systems have to deal with (i) availability of high frequency power conversion components, (ii) higher atmospheric loss, and (iii) overall efficiency in antenna arrays and the power conversion network. Different groups have proposed feedhorn based imaging arrays at W-band [1]. Though feedhorns have excellent performance, their mass, size, and expense make them unsuitable for large arrays.

In this paper we present a new compact, scalable, and low cost technology for efficient receiving of power using RF waves at 94 GHz. This technology employs a highly innovative array of slot antennas that is integrated on substrate composed of gold (Au), silicon (Si), and silicon dioxide (SiO_2) layers [2]. The length of the slots and spacing between them are optimized for a highly efficient beam through a 3-D electromagnetic simulation process. Antenna simulation results shows a good beam profile with very low side lobe levels and better than 93% antenna efficiency. Moreover, in this design architecture, the slots can be placed very close to each other enabling the integration of 20 X 20 slot array in an area that is slightly larger than one square centimeter. The RF to DC conversion of the power is done differentially by a very small network that is located adjacent to each individual slot. This network consists of a coupling electrode, bypass capacitors, matching transmission line, rectifier, a low pass filter, and a DC storage capacitor. This network is fabricated over the slot array using additional layers SiO_2 and Au which act as the dielectric and metal layers for the microstrip lines. Optimizing the losses for this network is achieved through iterative circuit simulations which factors in the thickness of the layers. Simulation results suggest that this technology is capable of realizing overall conversion efficiencies that are better than 72% and energy densities as high as 1.2W per square centimeter. This power density is 30 times better than high efficiency solar arrays with power density of 40 mW per square centimeter [3].

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Slot Antenna Array Design

A highly desirable solution to the efficient wireless power transfer would be to fabricate monolithic array of antenna-coupled detectors on a planar substrate [4]. However, most planar antenna designs produce broad beam patterns, and therefore require substrate lenses or micro-machined horns for efficient coupling to the incoming beam [5]. This does not preclude their use in large arrays; however, manufacturing and assembly of such arrays are not straight forward. For this work we came up with a novel dual-polarization planar T-slot antenna array which produces quite a narrow beam with no additional optical coupling elements. The output from the antenna array is two thin-film microstrip lines, one for each polarization, which can be efficiently coupled to Schottky diode detectors and associated circuits to produce a single pixel in an wireless RF to DC power transfer focal plane array.

Fig. 1 shows the general concept for the dual-polarized slot array antenna. The antenna is fabricated on a 550 um thick high dielectric silicon substrate ($\varepsilon_r = 11.8$) which is illuminated through substrate side to take advantage of the stronger antenna response on the dielectric side [6]. We also used a quarter wave thick quartz anti-reflection coating on the silicon substrate. The key features of the design are the slot length (L), slot width (W), and the slot separation (S) as shown in Fig. 1. Since the substrate is relatively thick and there are no coupling lenses, it is very important to keep the slot separation distance such that not to excite grating lobes within the frequency band of interest. The antenna was designed and simulated using Ansoft's High Frequency Structure Simulator (HFSS) – a 3D electromagnetic solver. The slots are used at their second resonance, and the impedance at the second resonance was approximately 22 Ohm. Fig. 2 shows the radiation pattern and the E- and H-plane cuts for the antenna pattern.

Differential RF to DC Converting Circuit

The differential RF to DC conversion circuit is shown in Fig. 3 (left). It consists of bypass capacitors, matching networks, diode rectifier, a blocking low pass filter, and a DC storage capacitor. The circuit receives differential RF signal from two slots of the antenna that are offset by 180 degrees from each other. A rectenna element is defined as the combination of this circuit and the pair of the slot antennas. The matched network enables conjugate matching the antenna impedance to the diode impedance for the optimum power transfer. The rectifier breaks the symmetry of the RF signal and the combination of the low pass filter and DC capacitor collects the DC component of the RF voltage across the rectifier.

Critical issues of this circuit are the losses across the transmission lines, turn-on voltage of the diode, and the speed of the rectifier – all of which ultimately impact the sensitivity and conversion efficiency of the rectenna. To minimize the transmission line losses, in our design as shown in Fig. 3, we used a combination of thick SiO_2 dielectric and gold as conductor to make the transmission lines and the capacitors on the T-slot antenna substrate.

GaAs Schottky barrier diodes (SBD), such as the one in Fig. 3 (right), are most commonly used for rectenna rectifier circuits. However zero barrier diodes with very low turn on voltage have gained popularity as a new type of diodes that enable higher sensitivity and enhance efficiency for the W-band rectenna circuits and terahertz imaging applications at the lower end of the power spectrum [7]. At the same time Si Schottky barrier diodes are catching up with the GaAs diodes in terms of speed and performance, at least in the 100 GHz frequency range. There are two main advantages of using Si based SBD's; (i) they are available as an device element in many high speed SiGe BICMOS process technologies from various foundries and (ii) they can be added to the rectenna through 3-D integration. Hence, same Si technology used for integration of the rectifiers can also be easily used for integration of the other housekeeping electronics for the wireless power transfer receiver including the power distribution as discussed in the next section.

Power Management

Efficient wireless power transfer technology requires efficient power management approach which provides modular and scalability of the power transfer receiver design. Power management section regulates the output voltage of receiver tile. Additional functions specific to the power management section is “peak power tracking” (PPT) that guarantees the stability of the power systems. This is because similar to solar arrays, at any given time, operating the wireless power receiver at power levels below the peak power will cause the collapse of the voltage across the rectenna array. To prevent this, the PPT circuit constantly measures the peak power of the rectenna (as a function of the RF input power) and allows the rectenna array to only operate at power levels that are below or equal to its peak power delivery capability.

There are several options we are considering for realizing the power management section: (i) it can be developed using plain CMOS technology, (ii) could be combined with the high speed Schottky barrier diode and integrated using SiGe BiCMOS technology, or (iii) it can be combined with GaAs Schottky diode and integrated using GaAs fabrication processing. While using the first option produces the least complex power system design, the second option provides us with the least complex path for wafer scale 3-D integration, which is the ultimate aim of this endeavor.

Discussions

We have designed and fabricated a novel T-Slot antenna coupled rectenna array at 94 GHz for demonstrating efficient wireless power transfer in this frequency band. Assembly and testing of these devices are under progress now, and are showing great promise.

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Figures

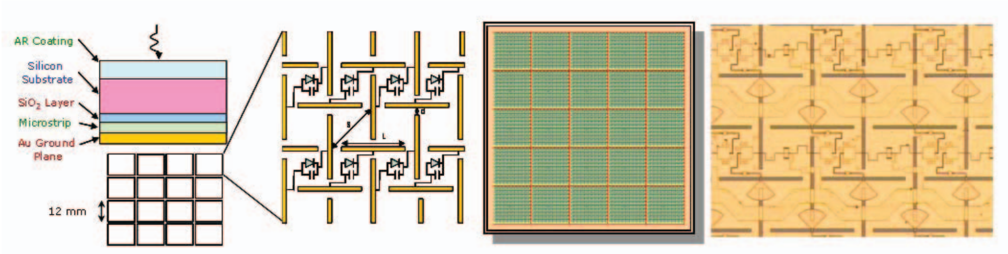

Fig. 1: Schematic diagram of the slot antenna array showing the slots for one pixel. Slot length “L” and the distance “d” sets the slot separation distance “S”. The cross-section of the pixel geometry is shown on top left. The figure in the middle shows the mask layout, and the figure on right shows a photograph of the fabricated T-slot antenna array.

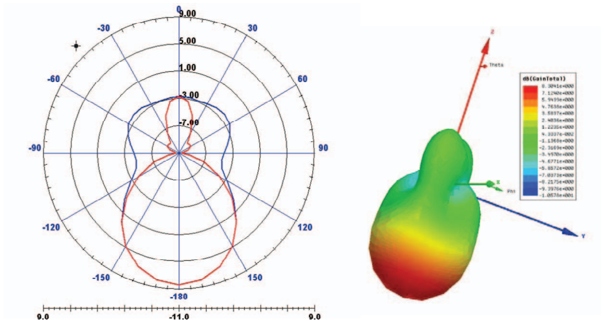

Fig. 2: Simulated E- and H-plane cut of the radiation pattern of the T-slot array antenna (left) and the 3-D radiation pattern of the array (right).

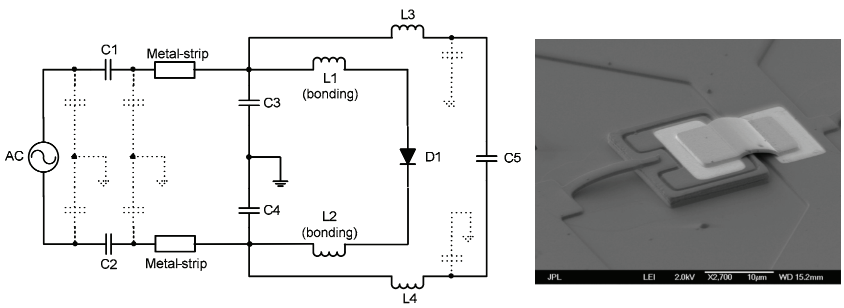

Fig. 3: RF to DC differential conversion circuit where using a single diode and using appropriate level shifting circuit, higher efficiency is achieved (left), and photograph of a GaAs Schottky diode fabricated at our laboratory at JPL (right). Similar diode is being used for our circuit.